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Funding liquidity constraints and the forward premium anomaly in a DSGE model

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ABSTRACT

This paper investigates the role of a funding liquidity constraint in the forward premium anomaly by developing a two-sector, two-agent dynamic stochastic general equilibrium (DSGE) model. We show that international consumption risks are not perfectly shared owing to the presence of a funding constraint and various discount factors. We explicitly specify a risk premium term and measure it in response to negative productivity shocks, policy shocks, and exchange rate shocks. The results indicate that these shocks, especially the policy shocks, widen the uncovered interest parity deviations to a great extent. Our research is compatible with the empirical evidence that funding illiquidity led to a significant uncovered interest parity violation during the 2008–2009 financial crisis.

1. Introduction

The uncovered interest parity (UIP) puzzle is one of the most extensively explored topics in international finance. UIP predicts that the short-term interest rate differential between domestic and foreign countries is positively associated with the subsequent exchange rate changes. Investors who would like to take advantage of interest rate differentials can use a forex forward contract to avoid exchange rate risks. The latter scenario forms the covered interest parity (CIP) condition. When CIP holds, the arbitrage is riskless and yields no profit. However, empirical evidence[1] indicates that high-interest-rate currencies tend to appreciate rather than depreciate, implying that positive excess returns exist in high-interest-rate currencies.

Substantial and persistent deviations from UIP or CIP during the recent financial crisis of 2008–2009 are observed in the literature[2]. Brunnermeier, Nagel, and Pedersen (2009) use the Chicago Board Options Exchange Volatility Index (CBOE VIX) and the TED spread as indicators of funding liquidity risks to examine the relationship between carry trade returns and currency crash risks[3]. Their results suggest that higher volatility and greater TED spreads reduce capital availability. As a consequence, liquidity-constrained speculators unwind their positions, hazarding currency stability. These liquidity spirals deviate the exchange rate from its fundamental value and

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[1] Some seminal contributions include Hansen and Hodrick (1980), Baillie, Lippens, and McMahon (1983), Baillie and Bollerslev (2000), Fama (1984), McCallum (1994), Burnside, Eichenbaum, Kleshchelski, and Rebelo (2006), as well as Roche and Moore (2012).

[2] Baba and Packer (2009), Coffey, Hrung, and Sarkar (2009), Hui et al. (2011), as well as Mancini Griffoli and Ranaldo (2012).

[3] VIX measures the implied volatility of S&P 500 index options. TED spread is defined as the difference between the three-month London Interbank Offered Rate (LIBOR) Eurodollar rate and the three-month T-Bill rate. A widened TED spread usually refers to liquidity tightening in the uncollateralized interbank lending market.

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prevent high-interest-rate currencies from depreciating, creating a scenario in which UIP does not hold. Hui, Genberg, and Chung (2011) and Mancini Griffoli and Ranaldo (2012) also empirically document the importance of a funding liquidity constraint in explaining the arbitrage deviations.

Previous research provides consistent empirical evidence regarding the existence of insufficient funding liquidity in the forward premium anomaly. Yet, a solid theoretical framework involving a funding liquidity constraint and its risk premium is still scarce. The first contribution of our paper is to fill this gap. Unlike existing studies[4] that use home bias or specific preferences in consumption to account for the UIP puzzle, we incorporate a funding liquidity constraint into an open-economy dynamic stochastic general equilibrium (DSGE) model. Our model is built with heterogeneous agents (borrowers and lenders) and two sectors (tradable goods and non-traded goods). It focuses on secured funding, which requires market participants to pledge collateralized securities for loans in foreign exchange transactions[5]. We draw the insight from Brandt, Cochrane, and Santa-Clara (2006) that incomplete international risk sharing and nominal rigidities widen the deviations from UIP. The former is characterized by the assumptions that agents have different discount factors and impatient agents are collateral-constrained. The latter is addressed by a Calvo-type price stickiness setting in both sectors.

In our model, domestic households are assumed to be less patient than foreign households, borrowing against non-traded goods for loans. In the steady state, domestic agents are indebted and domestic interest rates (loan rates) exceed foreign interest rates (deposit rates). The reason why we set up a two-country world with domestic households as borrowers and foreign households as savers is to provide a parsimonious way to analyze the role of collateral constraint in the UIP deviation[6]. We aim to show that international consumption risks are not perfectly shared owing to the presence of a collateral constraint and credit spreads associated with different discount factors.

The basic mechanism of our model works as follows. Domestic households choose to borrow abroad or from the domestic government. In our setup, domestic agents will be inclined to borrow from abroad since the foreign interest rate is lower. The costs of borrowing abroad include future appreciation of foreign currency and a credit risk premium charged to the collateral-constrained borrowers. Domestic agents borrow foreign currency and use it to finance tradable and non-traded consumption denominated in domestic currency. During recessions the available collateralized loans are scarce due to either the lender's perception of an increase in the degree of credit market risk or a shrinkage in the borrower's pledged capital (Mancini Griffoli & Ranaldo, 2012). Trade volume is reduced, and transactions take place with larger credit spreads. We exploit the reasoning that tightened funding liquidity restricts free movement of capital and results in a failure of UIP[7]. In the real world, securities firms such as hedge funds, commercial banks and investment banks mostly rely on collateralized borrowing to finance their trading activities. Brunnermeier and Pedersen (2009) provide a rich description of traders' funding requirements. Their research predicts that a decrease in capital reduces market liquidity and increases margins[8] as well as risk premiums.

Another contribution of our paper is that we explicitly specify a risk premium term, which is commonly alluded to as an error term or an intercept in most empirical studies[9]. The risk premium in our model is dependent on the intertemporal marginal rate of substitution in consumption, the discount factor, expected inflation of tradable goods, a multiplier of the collateral constraint, and a differential between domestic and foreign interest rates. In response to exogenous shocks, the interactions between these macroeconomic variables generate time-varying risk premiums.

Several studies also introduce risk premiums in DSGE models. For example, Rudebusch and Swanson (2008) consider habit-based consumption, quadratic labor adjustment costs, real wage rigidities, and staggered nominal wage contraction in a DSGE model to fit the term premium on long-term bonds. Andreasen (2012) analyzes the effects of rare disasters and uncertainty shocks on the variation of risk premiums in DSGE models approximated to the second and third orders. In both papers, the risk premium is expressed as the difference between the return of an asset and the unobserved risk-free return of the same asset. García and González (2013) lay out a risk premium term related to a risk premium shock, external-debt-to-GDP ratio, and the real exchange rate. In their model, the risk premium shock is a driving source of credit frictions in the international capital market. Their paper aims to examine the exchange rate dynamics in response to risk premium shocks and commodity price shocks. Nevertheless, the aforementioned papers omit the presence of a collateral constraint and do not provide detailed discussions of the forward premium anomaly.

Our main results are summarized as follows. First, a tightening of the collateral constraint widens UIP deviations. Negative productivity shocks tighten the collateral constraint and reduce domestic borrowing along with current consumption. This corroborates the empirical evidence that a funding liquidity constraint was an important cause of UIP violations during the most recent financial crisis. Second, depreciation shocks on domestic currency increase the differential between foreign and domestic interest rates and lead to a moderately negative UIP deviation. Third, policy shocks resulting from raising domestic interest rates cause a substantially negative UIP deviation. Overall, a negative UIP deviation is associated with a widened interest rate differential, a less tightened collateral

[4] Gavazzoni (2009), Bansal and Shaliastovich (2013), Benigno et al. (2012), Gourio et al. (2013), as well as Colacito and Croce (2013).

[5] Hereafter, we will use funding constraint and collateral constraint interchangeably.

[6] In an alternate setting, each county could have borrowers and savers. This would require defining loan and deposit rates in both countries, which adds complexity to the model without significantly improving the understanding of the issue.

[7] Mitchell, Pedersen, and Pulvino (2007) study the effect of slow moving capital on arbitrage. Brunnermeier et al. (2009) discuss the relationship between liquidity constraints and currency crashes. Engel (2013) also mentions that the presence of a collateral constraint can cause a UIP deviation.

[8] A margin is defined as the difference between the security's price and its collateralized value.

[9] Zhou and Kutan (2005), Li et al. (2012), Ding (2012), and Lee (2013).

constraint, lower tradable inflation, and a lower intertemporal marginal rate of substitution between current consumption and next-period consumption. Notwithstanding that our paper focuses on collateralized borrowing, this finding provides the same implication with uncollateralized loans. Monetary contraction narrows the TED spread and signals less liquidity strains in the short-term inter-bank money market.

The remainder of this paper is organized as follows. Section 2 provides a brief summary of related literature. Section 3 describes our model. Section 4 presents calibration results, and Section 5 concludes.

2. Related literature

There is abundant literature illustrating deviations from uncovered interest parity from the aspect of risk premium. We will introduce uncovered interest parity and then outline related studies. With exchange rate defined as the price of foreign currency in units of domestic currency, let s_t denote the log value of an exchange rate. An increase in s_t represents the depreciation of domestic currency. i_t is the nominal interest rate. An asterisk stands for the foreign country. ζ_{t+1} is the error term. If UIP holds, the coefficient of the interest-rate differential in Eq. (1) should be one. However, in empirical studies b is usually found to be less than one or even negative.

$$E_t s_{t+1} - s_t = a + b\left(i_t - i_t^*\right) + \zeta_{t+1} \tag{1}$$

Foreign exchange risk premium is one of the prevailing reasons for UIP violations (Engel, 2013; Froot & Thaler, 1990; Lewis, 1995). To explain this, Fama (1984) decomposes the definition of forward premium (2) into Eq. (3).

$$f_t - s_t = i_t - i_t^* \tag{2}$$

$$\left(f_t - E_t s_{t+1}\right) + \left(E_t s_{t+1} - s_t\right) = i_t - i_t^* \tag{3}$$

where f_t is the forward exchange rate and E_t is the expectation operator conditional on information available at time t. The first term on the left-hand side in Eq. (3) is the currency risk premium, and the second term is the expected depreciation. Since high-interest-rate currency is riskier, an excess premium $f_t - E_t s_{t+1}$ will be offered as risk compensation.

Backus, Gavazzoni, Telmer, and Zin (2010) characterize monetary policies with foreign and domestic Taylor rules to examine the puzzle. Using Lucas's (1982) nominal pricing kernels, they find that exchange rate fluctuations in complete financial markets equal the nominal marginal rate of substitution of a domestic country relative to a foreign country. This suggests that monetary policy rules associated with pricing kernels are in accord with carry trade evidence. Carry traders borrow currencies from a low-interest-rate country and lend them to a high-interest-rate country. Central banks, however, implement monetary policies in the opposite direction, borrowing high yielding currencies to invest in low yielding currencies.

Benigno, Benigno, and Nistico (2012) conduct a Vector Autoregressive (VAR) analysis and propose that increasing the volatilities of the nominal shocks causes substantial dispersion in the risk premium. They build a two-country model with time-varying uncertainty to reproduce a negative slope coefficient in the UIP regression. In their model, domestic and foreign agents have different Epstein and Zin (1989) preferences, the asset market is complete, and firms produce in a monopolistically competitive market with Calvo-type price settings. Closed by a Taylor-type interest rate rule, the model is analyzed with productivity shocks, policy shocks, and inflation-target shocks, defined as the deviation of the gross producer inflation from a target instituted by policymakers. They conclude that a high degree of interest-rate smoothing, price stickiness, and Epstein–Zin preferences are the key elements to capture a negative UIP slope coefficient.

Gourio, Siemer, and Verdelhan (2013) develop a two-country, one-good model that is embedded with both recursive preferences and a time-varying aggregate risk measured by the probability of exposure to a worldwide economic disaster. With the assumptions of purchasing power parity and complete international financial markets, they show that variations in the probability of disaster explain the failure of UIP. A higher probability of being exposed to the world risk generates a larger exchange rate risk premium and a negative UIP slope coefficient.

Empirical evidence of the forward premium anomaly is mixed. Bansal and Dahlquist (2000) use country-specific information from 28 economies to examine the UIP puzzle. Their conclusions imply that UIP holds for emerging economies and lower-income developed economies. Moreover, the puzzle resulting from time-varying risk premiums is related to each country's GNP per capita, average inflation, inflation volatility, and credit risk rating. Alexius (2001) chooses 13 OECD countries and tests UIP on their long-term government bond yields as well as their exchange rates with the United States. Taking the time-varying durations of a coupon bond into account, both ordinary least squares and instrument variable results support the UIP hypothesis in more than half of the countries.

Chaboud and Wright (2005) start with a UIP regression on the U.S. dollar against several major currencies at a daily frequency. The UIP hypothesis is significantly rejected. Nevertheless, when intradaily data from 16:30 to 21:00 New York time are used, the results become consistent with the UIP hypothesis. They exploit the fact that intradaily interest differentials are zero. Consequently, over short time horizons the risk premium is small and the slope coefficient in the UIP equation might be close to one. Li, Ghoshray, and Morley (2012) use the component GARCH-in-mean model to measure the time-varying risk premium in UIP. Their results suggest that risk premium is an important determinant for analyzing the exchange rate dynamics for most developed and emerging countries.

Hui et al. (2011) examine the role of funding liquidity risk in the CIP deviations. They find that before the bankruptcy of Lehman Brothers, the CIP deviations can be explained by funding liquidity risk, measured by the spread between LIBOR and the overnight index swap (OIS) rate, in the European, Japanese, British, Hong Kong, Singaporean, and Swiss economies. After Lehman Brothers' failure, both counterparty risk[10] and funding liquidity risk become major determinants for CIP deviations in the European markets.

Mancini Griffoli and Ranaldo (2012) measure the deviations from secured and unsecured arbitrage strategies during the crisis. They propose three causes of liquidity constraints: lenders' deleveraging imperatives, lenders' prudential hoarding, and borrowers' limited pledged capital in exchange for liquidity. Using the balance sheet size of financial intermediaries, banks' excess reserves deposited at Federal Reserve Banks, and the spread between Agency MBS and General Collateral (GC) repo rates as proxies for funding liquidity, they obtain results indicating that a lack of U.S. dollar funding liquidity can explain the failure of the CIP condition during the crisis.

3. Model

We extend Monacelli's (2009) model[11] to a two-country, two-sector economy with heterogeneous agents and sluggish price adjustment for market frictions. Representative agents in the home country are assumed to be less patient than those in the foreign country. Households in each country share the same preferences, consuming a CES composite of home tradable goods, foreign tradable goods, and services from non-traded goods. Domestic households face an optimization problem that includes a budget constraint and a collateral constraint. Foreign households have accumulated sufficient wealth and are not credit-constrained. Non-traded goods are pledged for loans. They can be considered as securities issued by domestic dealers and cannot be traded across borders[12]. Labor is immobile between countries. Domestic firms in the tradable goods and non-traded goods sectors produce intermediate goods with labor in a monopolistically competitive market. The final goods market is assumed to be perfectly competitive.

3.1. Households in the home country

The preferences of the representative agents in the home country are defined over a composite consumption, consisting of tradable goods C_t, non-traded goods D_t and disutility of employment N_t.

$$X_t = \left[(1-\alpha)^{\frac{1}{\eta}}(C_t)^{\frac{\eta-1}{\eta}} + \alpha^{\frac{1}{\eta}}(D_t)^{\frac{\eta-1}{\eta}}\right]^{\frac{\eta}{\eta-1}} \tag{4}$$

$$C_t = \left[(1-\alpha_C)^{\frac{1}{\varepsilon}}\left(C_{H,t}\right)^{\frac{\varepsilon-1}{\varepsilon}} + (\alpha_C)^{\frac{1}{\varepsilon}}\left(C_{F,t}\right)^{\frac{\varepsilon-1}{\varepsilon}}\right]^{\frac{\varepsilon}{\varepsilon-1}} \tag{5}$$

Here η is the elasticity of substitution between tradable goods and non-traded goods, and ε is the elasticity of substitution between domestic goods $C_{H,t}$ and foreign goods $C_{F,t}$. α determines the steady-state share of non-traded goods in total consumption. α_c is the steady-state share of foreign goods in tradable goods consumption. The objective of the representative agents in the home country is to maximize the expected present discounted utility (6) subject to the budget constraint (7) and the collateral constraint (8) in real terms.

$$Max\, E_0\left\{\sum_{t=0}^{\infty}\beta^t\left[\ln X_t - \frac{(N_t)^{1+\varsigma}}{1+\varsigma}\right]\right\} \tag{6}$$

s.t.

$$C_t + Q_t(D_t-(1-\delta)D_{t-1}) + (1+r_{t-1})\frac{b_{t-1}}{\pi_{C,t}} + \left(1+r^*_{t-1}\right)\frac{S_t b^*_{t-1}}{\pi_{C,t}} + \frac{T_t}{P_{C,t}} = b_t + S_t b^*_t + w_t N_t, \tag{7}$$

$$(1+r_t)b_t + \left(1+r^*_t\right)S_t b^*_t = (1-\chi)(1-\delta)E_t\left\{D_t Q_{t+1}\pi_{C,t+1}\right\}, \tag{8}$$

[10] Counterparty risk refers to the risk that the other party in the contract may default.

[11] Monacelli (2009) discusses the co-movement problem between tradable goods and durable goods with the presence of collateral-constrained households. In his closed-economy model, durable goods are secured for loans.

[12] In practice, most countries impose regulations on selling securities abroad. Securities are not traded as easily as regular consumption goods. We made this assumption for simplicity. Including a tradable security should not substantially change the results.

where β is the discount factor. r_t and r_t^* define the real cost of domestic borrowing and foreign borrowing, respectively. ς is the elasticity of marginal disutility with respect to labor supply. δ is the depreciation rate of non-traded goods. Q_t is the relative price of non-traded goods in terms of tradable goods, defined as P_D/P_C. Households hold domestic borrowing $b_t = B_t / P_{C,t}$ from the government and foreign borrowing $b_t^* = B_t^*/P_{C,t}$. $w_t = W_t/P_{C,t}$ represents the real wage. $\pi_{C,t} = P_{C,t}/P_{C,t-1}$ is the domestic inflation rate of tradable goods. T_t represents the lump-sum taxes. S_t defines the nominal exchange rate. An increase in S_t represents the depreciation of domestic currency. χ represents the fraction of the value of non-traded goods that cannot be used as collateral for a loan. The first order conditions are defined by Eqs. (9)–(13).

$$U_{C,t} = \gamma_t \tag{9}$$

$$-\zeta U_{N,t} = U_{C,t} \cdot w_t \tag{10}$$

$$\varphi_t(1+r_t) = 1-\beta E_t\left\{\frac{U_{C,t+1}}{U_{C,t}} \cdot \frac{(1+r_t)}{\pi_{C,t+1}}\right\} \tag{11}$$

$$Q_t U_{C,t} = U_{D,t} + \beta(1-\delta)E_t\left\{U_{C,t+1}Q_{t+1}\right\} + (1-\chi)(1-\delta)U_{C,t}Q_t\varphi_t E_t\pi_{D,t+1} \tag{12}$$

$$\left(1+r_t^*\right) = (1+r_t)\cdot\frac{S_t^{\,t}}{E_tS_{t+1}} + \frac{U_{C,t}}{\beta\; E_tU_{C,t+1}}\varphi_t\pi_{C,t+1}\left(r_t-r_t^*\right) \tag{13}$$

The utility function follows the assumptions that $U' > 0$ and $U'' < 0$. Eq. (10) shows the trade-off between consumption and labor choice. Eq. (11) is the intertemporal Euler equation and implies that $\beta + \overline{\varphi} = 1/(1+\overline{r})$ in the steady state. Eq. (12) states that the benefit of obtaining an additional unit of non-traded goods at time t must equal the marginal utility of tradable goods consumption at time t. The former consists of the direct utility from non-traded goods, the utility of future tradable goods consumption from selling the non-traded goods at $t+1$, and the utility obtained from borrowing against non-traded goods.

γ_t and $\gamma_t\varphi_t$ are multipliers for budget constraint and collateral constraint, respectively. The second term on the right-hand side of Eq. (13) is defined as a UIP deviation[13] and denoted as λ_t. The friction causing the UIP deviation is the presence of a collateral constraint, which enters Eq. (13) by φ_t. A greater value of φ_t refers to a tightening of the collateral constraint. In response to different shocks, the interactions between intertemporal marginal rate of substitution in consumption, expected inflation rate, and interest rate spreads determine the sign of the UIP deviation, denoted by λ_t.

Eq. (13) can characterize the empirical uncovered interest parity puzzle. When $r_t > r_t^*$, a negative λ_t implies that domestic currency is expected to depreciate less, or even appreciate. A positive λ_t implies that domestic currency is expected to depreciate more than a zero UIP deviation. In the latter case, the costs of borrowing abroad include the future appreciation of foreign currency and a credit risk premium charged to the collateral-constrained borrowers. During a crisis, the capital availability is limited and the potential spreads between domestic rates and foreign rates widen. To restore the parity implied by Eq. (13), a larger depreciation is accordingly needed. Other things being equal, both the tightening of collateral constraint (greater φ_t) and a greater marginal rate of substitution between current consumption and next-period consumption lead to an increase in the UIP deviation.

3.2. Households in the foreign country

The objective of the representative agent in the foreign country is to maximize the expected present discounted utility (14) subject to the budget constraint (15) in real terms.

$$Max\;\; E_0\left\{\sum_{t=0}^{\infty}\tilde{\beta}^t\left[\ln X_t^* - \frac{(N_t^*)^{1+\varsigma}}{1+\varsigma}\right]\right\} \tag{14}$$

$$s.t.\quad C_t^* + Q_t^*\left(D_t^*-(1-\delta)D_{t-1}^*\right) + \left(b_t^{G^*} + S_tb_t^*\right) + \frac{T_t^*}{P_{C,t}^*} = \frac{(1+r_{t-1}^*)S_tb_{t-1}^* + \left(1+r_{t-1}^{G^*}\right)b_{t-1}^{G^*}}{\pi_{C,t}^*} + w_t^*N_t^*, \tag{15}$$

[13] We follow Engel (2013) and define this term as a UIP deviation since it is a dispersion from the standard UIP condition. We thank the referee for this suggestion about defining the UIP deviation.

where $\tilde{\beta}$ is the discount factor for foreign households. Foreign savers can decide to provide loans to the government $b_t^{G\,*}$ with a return of $r_t^{G\,*}$ or to borrowers abroad defined as b_t^* with a return of r_t^*. The first order conditions are defined in Eqs. (16)–(19). Eqs. (17) and (18) imply that $\tilde{\beta} = 1/(1+\overline{r}^*)$ and $\overline{r}^* = \overline{r}^{G*}$ in the steady state.

$$-\zeta\ U_{N_t^*} = U_{C_t^*} \cdot w_t^* \tag{16}$$

$$\tilde{\beta}\left(1+r_t^{G*}\right) \cdot \frac{1}{\pi_{C,t+1}^*} = \frac{U_{C^*,t}}{U_{C^*,t+1}} \tag{17}$$

$$\tilde{\beta}(1+r_t^*) \cdot \frac{S_{t+1}}{S_t \pi_{C,t+1}^*} = \frac{U_{C^*,t}}{U_{C^*,t+1}} \tag{18}$$

$$Q_t^* U_{C^*,t} = U_{D^*,t} + \tilde{\beta} E_t\left\{U_{C^*,t+1} Q_{t+1}^*\right\} \tag{19}$$

Combining Eqs. (11), (17) and (18) leads to Eq. (20), where $MRS_{t+1} = UC_{,t+1} / U_{C,t}$ and $MRS_{t+1}^* = U_{C^*,t+1}/U_{C^*,t}$. It is noted that consumption risks, defined by the marginal utility growth between domestic and foreign markets, are not completely shared due to the presence of a collateral constraint and different discount factors[14].

$$\frac{1}{[1-\varphi_t(1+r_t)]} = \frac{\tilde{\beta}}{\beta} \cdot \frac{MRS_{t+1}^* \pi_{C,t+1}}{MRS_{t+1} \pi_{C,t+1}^*} \cdot \frac{(1+r_t^*)}{(1+r_t)} \tag{20}$$

3.3. Retailers and intermediate goods producers

Retailers sell final goods to consumers in a perfectly competitive market. The production function for domestic retailers in tradable goods sector C and non-traded goods sector D is defined as

$$Y_{l,t} = \left[\sum_{j=1}^{n} \left(Y_{l,t}^j\right)^{1-\theta}\right]^{\frac{1}{1-\theta}}, \quad l = C, D, \tag{21}$$

where θ refers to the elasticity of substitution between any two differentiated goods and is assumed to be the same in both sectors. Intermediate goods firms in non-traded and tradable goods sectors produce with labor in a monopolistically competitive market. The production function for an individual firm is defined in Eq. (22). Z_t is the productivity shock.

$$Y_{l,t}^j = Z_t N_{l,t}^j \quad l = C, D \tag{22}$$

Each firm charges a price mark-up over its nominal marginal cost. During each period only a fraction $1-\nu$ of all firms can adjust their prices. ν is a measure of the degree of nominal rigidity. Each firm faces a constant elasticity demand curve and identical marginal costs. Eqs. (23) and (24) represent the marginal costs in both sectors. Let x_t denote the percentage deviation of a variable X_t around its steady state. The Phillips curves for tradable goods and non-traded goods can be derived as Eqs. (25) and (26).

$$MC_{C,t} = \frac{W_t/P_{C,t}}{Z_t} \tag{23}$$

$$MC_{D,t} = \frac{W_t/P_{D,t}}{Z_t Q_t} \tag{24}$$

$$\pi_{C,t} = \beta E_t \pi_{C,t+1} + \frac{(1-\nu)\cdot(1-\beta\nu)}{\nu} \cdot (w_t - z_t) \tag{25}$$

$$\pi_{D,t} = \beta E_t \pi_{D,t+1} + \frac{(1-\nu)\cdot(1-\beta\nu)}{\nu} \cdot (w_t - z_t - q_t) \tag{26}$$

14 Lucas (1982) international asset pricing model documents a complete-risk-sharing condition under uncovered interest parity as $\frac{S_{t+1}}{S_t} = \frac{MRS^*_{t+1}\pi_{C,t+1}}{MRS_{t+1}\pi^*_{C,\,t+1}}$.

Table 1
Baseline parameters.

Baseline parameters	Values	Description
$\tilde{\beta}$	0.99	Discount factor of foreign households
β	0.98	Discount factor of domestic households
δ	0.01	Depreciation rate of non-traded goods
χ	0.25	Fraction of the value of non-traded goods that cannot be used as collateral
$\alpha = \alpha^*$	0.2	The share of non-traded goods in total consumption
$\alpha_C = \alpha_C^*$	0.2	The share of foreign goods in tradable goods consumption
θ	6	The elasticity of substitution between any two differentiated goods
η	1	The elasticity of substitution between tradable and non-traded goods
ζ	1	The elasticity of marginal disutility with respect to labor supply
ε	1	The elasticity of substitution between domestic goods and foreign goods
ν	0.75	The degree of nominal rigidity
ρ	0.95	The persistence of policy shocks
ρ_r	0.8	The weight imposed on the lagged policy rate
ρ_Y	0.2	The weight imposed on the lagged inflation rate and output gap
κ_π	1.5	Coefficient of inflation in the Taylor rule
κ_Y	0.5	Coefficient of the output gap in the Taylor rule

3.4. Government sectors

The fiscal authority collects taxes in order to make loans to domestic borrowers. The real budget constraints for domestic government and foreign government are defined as (27) and (28), respectively.

$$b_t - (1 + r_{t-1}) \frac{b_{t-1}}{\pi_{C,t}} = \frac{T_t}{P_{C,t}} \tag{27}$$

$$b_t^{G*} + \frac{T_t^*}{P_{C,t}^*} = \left(1 + r_{t-1}^{G*}\right) \frac{b_{t-1}^{G*}}{\pi_{C,t}^*} \tag{28}$$

The model is closed with a Taylor-type interest rate rule. We assume that the central bank sets the interest rate by responding to a lagged interest rate, lagged output gap and lagged aggregate inflation. A log-linear approximation of the interest rate rule around zero inflation is expressed as Eq. (29). ρ_r is the weight imposed on lagged interest rates. ρ_Y is the weight imposed on lagged inflation rates and output gaps. κ_π and κ_Y are the coefficients of inflation and output gap, respectively, in the Taylor rule.

$$r_t = \rho_r \cdot r_{t-1} + \rho_Y \cdot \left[\kappa_\pi \left[(1-\alpha)\pi_{C,t-1} + \alpha \pi_{D,t-1}\right] + \kappa_y y_{t-1}\right] + u_t \tag{29}$$

Table 2
Calibrated steady-state values.

Baseline parameters	Steady-state values	Description
$\overline{\varphi}$	0.00039	The multiplier on collateral constraint
$\overline{N} = \overline{N}^*$	0.66	Steady-state level of hours worked for each agent
$\overline{\pi}_C = \overline{\pi}_C^*$	1	Inflation rate of tradable goods
$\overline{Q} = \overline{Q}^*$	1	Relative price of durable goods
$\bar{O}$	1	Terms of trade
$\overline{S}$	1	Exchange rate
$\overline{r}$	1.02	Domestic interest rate
$\overline{r}^*$	1.01	Foreign interest rate
$\overline{\lambda}$	0.00000398	Deviation from the UIP condition
$\overline{C}$	0.593472	Tradable goods consumption in the home country
$\overline{C}^*$	0.5796	Tradable goods consumption in the foreign country
$\overline{D}$	6.652827	Durable goods consumption in the home country
$\overline{D}^*$	7.282116	Durable goods consumption in the foreign country
$\frac{\overline{b}}{\overline{D}}$	5.798479	Domestic borrowing relative to durable goods
$\frac{\overline{b}^*}{\overline{D}}$	−5.06333	Foreign borrowing relative to durable goods
$\frac{\overline{W}}{\overline{D}}$	0.073595	Real wages relative to durable goods in the home country
$\frac{\overline{W}^*}{\overline{D}^*}$	0.06567	Real wages relative to durable goods in the foreign country
$\overline{Y} = \overline{Y}^*$	0.66	Total production

Table 3
Calibration results.

Variables	Standard deviation			Variables	Standard deviation		
	Domestic productivity shocks	Policy shocks	Exchange rate shocks		Domestic productivity shocks	Policy shocks	Exchange rate shocks
C_t	0.1339	0.8700	0.2116	C_t^*	0.0456	0.8603	0.1043
D_t	0.0932	0.6050	0.1942	D_t^*	0.3244	1.6107	0.1752
b_t	0.0283	0.7683	0.0702	b_t^*	0.0283	0.7683	0.3771
r_t	0.0230	0.6768	0.0607	r_t^*	0.0449	0.4078	0.0799
Y_t	0.1207	0.2599	0.0237	Y_t^*	0.0305	0.4230	0.0875
Q_t	0.0995	0.9710	0.2441	Q_t^*	0.0882	0.9756	0.1211
$\pi_{C,t}$	0.0532	0.4988	0.0756	$\pi_{C,t}^*$	0.0521	0.5283	0.0598
$\pi_{D,t}$	0.0793	0.7070	0.0116	$\pi_{D,t}^*$	0.0421	0.4306	0.0997
w_t	0.2810	0.6147	0.2500	w_t^*	0.0804	1.0288	0.2649
λ_t	0.0000	0.0004	0.0000				
ϕ_t	0.0494	1.2922	0.0706				

The model is evaluated with domestic productivity shocks, policy shocks, and exchange rate shocks, defined in Eqs. (30)–(32). The shocks follow an exogenous $AR(1)$ process. m_{1t}, m_{2t}, and m_{3t} are assumed to be serially uncorrelated processes with zero means. ρ is assumed to be less than 1.

$$z_t = \rho z_{t-1} - m_{1t} \tag{30}$$

$$u_t = \rho u_{t-1} + m_{2t} \tag{31}$$

$$s_t = \rho s_{t-1} + m_{3t} \tag{32}$$

3.5. Equilibrium

Eq. (33) represents the market-clearing condition for the goods market. O_t refers to the terms of trade condition and is defined in Eq. (34). $P_{H,t}$ is the average price of domestically produced tradable goods, and $P_{F,t}$ is the average price of imported foreign goods. With complete exchange rate pass-through, the price of imported foreign goods equals the foreign price denominated in the domestic currency, that is, $P_{F,t} = S_t P_{H,t}^*$. The producer price level $P_{H,t}^*$ for the foreign country is assumed to be the same as its consumer price level $P_{C,t}^*$. Eqs. (35)–(36) are the equilibrium conditions for the labor market and bond market.

$$Y_t = (1-\alpha_C)C_t + D_t - (1-\delta)D_{t-1} + \alpha_C O_t Y_t^* \tag{33}$$

$$O_t = \frac{P_{F,t}}{P_{H,t}} = \frac{S_t P_{H,t}^*}{P_{H,t}} = \frac{S_t P_{C,t}^*}{P_{H,t}} \tag{34}$$

$$N_t = N_{C,t} + N_{D,t} \tag{35}$$

$$B_t + B_t^{G*} = S_t B_t^* \tag{36}$$

4. Calibration results

The baseline parameters are chosen according to previous studies (Monacelli, 2009). The discount factor $\tilde{\beta}$ for foreign households is 0.99, which implies an annual real deposit rate of 4%. The discount factor β for domestic households is 0.98, which implies an annual real loan rate of 8%. The depreciation rate of non-traded goods δ is 0.01, implying an annual rate of depreciation of 4%. χ, the fraction of the value of non-traded goods that cannot be used as collateral for a loan is 0.25. α and α_C, the steady-state share of non-traded goods in total consumption and the steady-state share of foreign goods in tradable goods consumption, respectively, are both 0.2. η and ς, the elasticity of substitution between tradable and non-traded goods and the elasticity of marginal disutility with respect to labor supply, respectively, are both equal to 1. ε, the elasticity of substitution between domestic goods and foreign goods, is assumed to be 1. The degree of nominal rigidity v is set equal to 0.75, implying that the expected time between price adjustments is one year. κ_π and κ_Y in the Taylor rule are assumed to be 1.5 and 0.5, respectively. ρ_r, the weight imposed on lagged policy rates, is assumed to be 0.8;

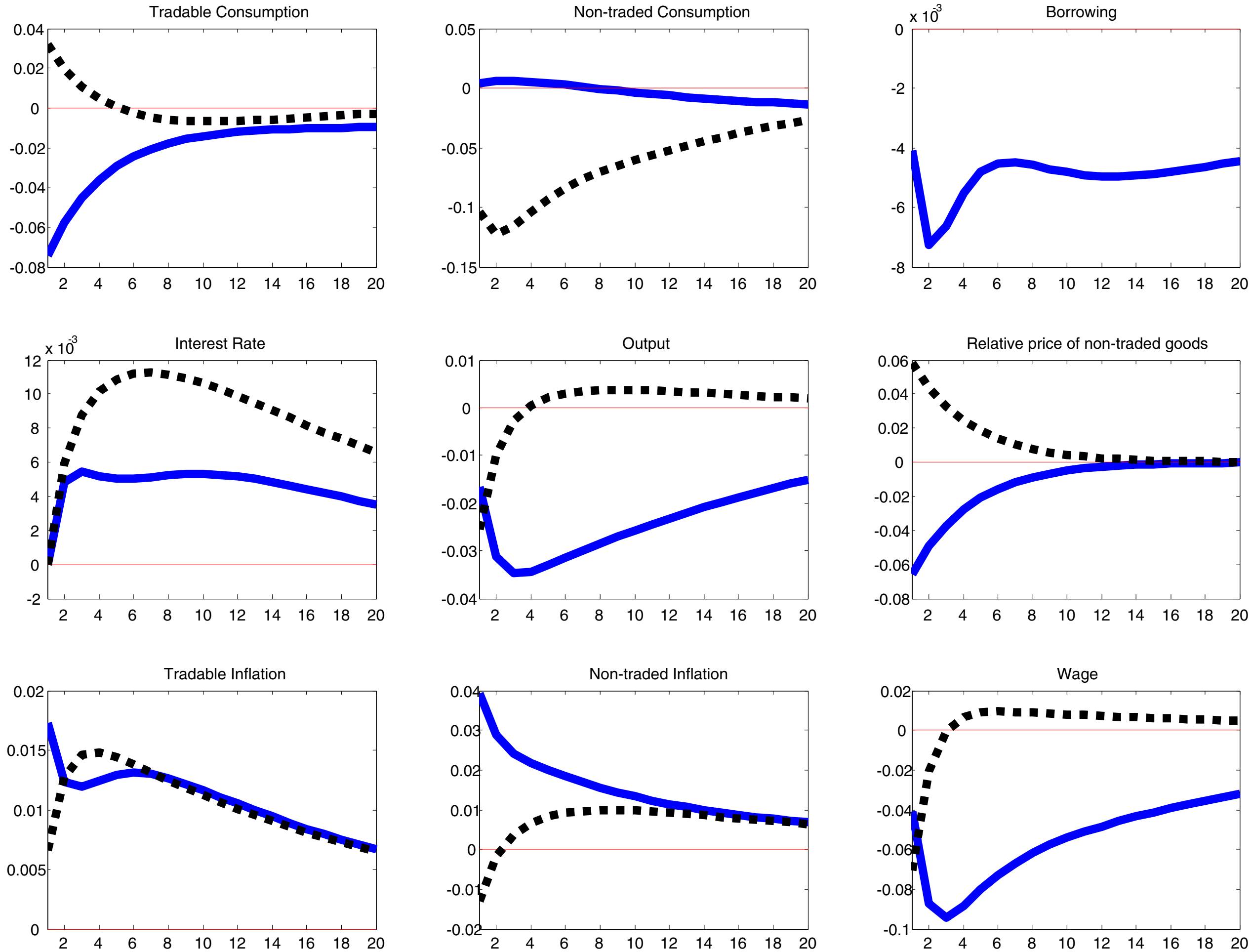

Fig. 1. Impulse responses to negative domestic productivity shocks (the solid line represents the domestic country and the dashed line represents the foreign country).

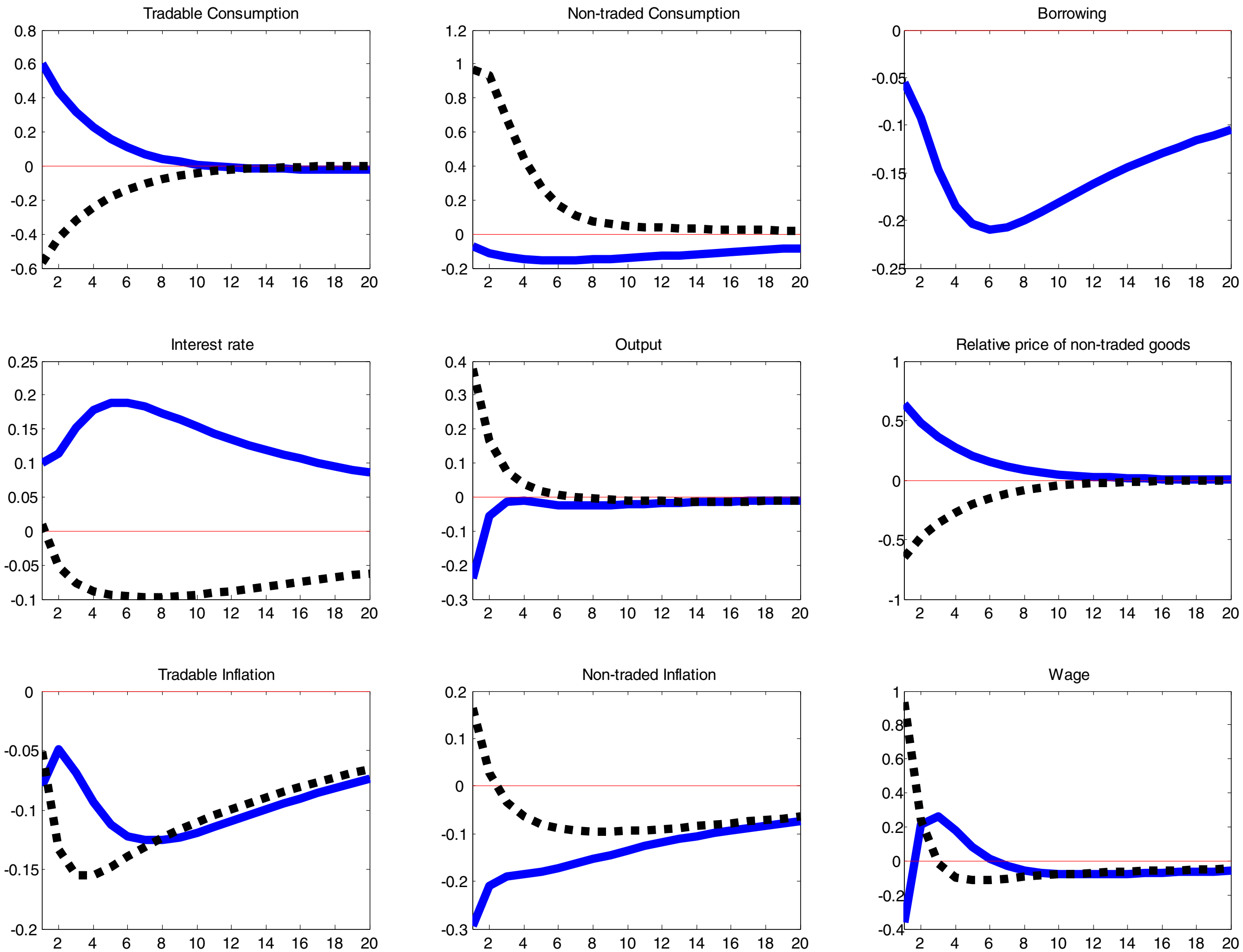

Fig. 2. Impulse responses to policy shocks (the solid line represents the domestic country and the dashed line represents the foreign country).

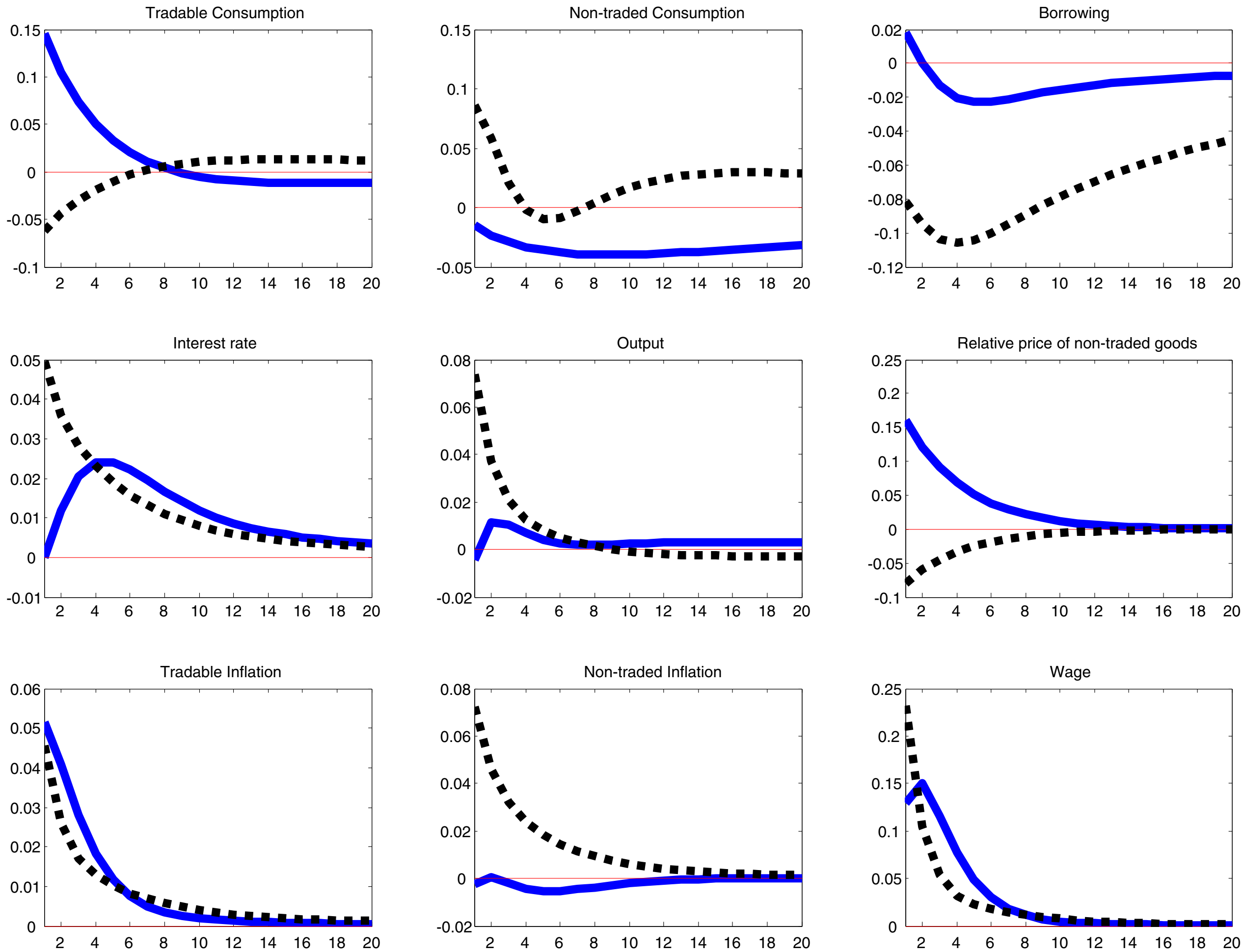

Fig. 3. Impulse responses to exchange rate shocks (the solid line represents the domestic country and the dashed line represents the foreign country).

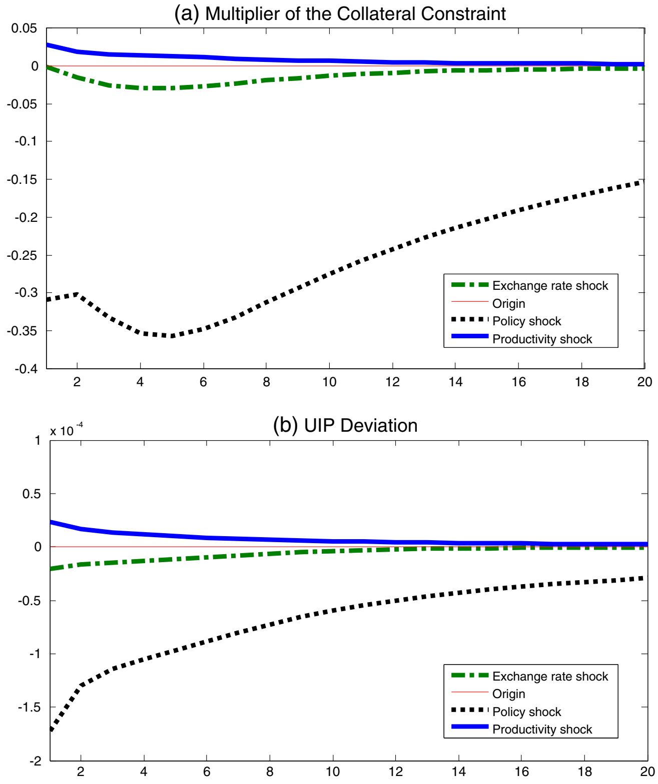

Fig. 4. Tightening of the collateral constraint and UIP deviation in response to different shocks.

ρ_Y, the weight imposed on lagged inflation rate and output gap, is 0.2. The persistence of policy shocks ρ is assumed to be 0.95. $\overline{q}$, the relative price of non-traded goods at steady state, is 1. The work hours $\overline{N}$ are parameterized to 0.33. Table 1 summarizes the baseline parameters. Table 2 presents the steady-state values of the variables. Table 3 presents the standard deviations of major variables responding to productivity shocks, policy shocks, and exchange rate shocks.

Fig. 1 depicts the impulse responses to ten-percent-standard-deviation negative productivity shocks. It indicates that tradable consumption, borrowing, output, wage, and the relative price of non-traded goods in the domestic country decline in response to negative productivity shocks. In line with empirical evidence, lower output and less capital availability are associated with recessions. Fig. 2 shows the dynamics of major variables in response to ten-percent-standard-deviation policy shocks. Monetary contraction depresses domestic wages, non-traded consumption and output. An increase in domestic interest rates has immediate adverse effects on expected inflation of tradable goods and that of non-traded goods. A higher domestic interest rate discourages collateral-constrained households from borrowing. In response to a relatively lower rate of return from lending, foreign households provide less funding to domestic households. These two effects result in decreased borrowing in equilibrium. A lower relative price of non-traded goods also induces foreign households to consume more non-traded goods.

Implementing exchange rate shocks aims to capture exogenous disturbances other than domestic policy shocks (monetary contraction) since there are no specifications about which exchange rate regime a country adopts in our model. Fig. 3 presents the impulse responses of major variables to ten-percent-standard-deviation exchange rate shocks. Domestic currency depreciation increases domestic borrowing, reduces the prices of tradable goods and boosts more aggregate tradable consumption. Foreign households switch resources from lending abroad to purchasing more non-traded goods and subsequently more tradable goods. Positive exchange rate shocks have no initial impact on domestic interest rates, but domestic interest rates gradually increase, responding to future domestic currency appreciation. Fig. 4 panel (a) illustrates the dynamics of collateral constraint multipliers. A tightening of the collateral constraint (a greater φ_t) that results from negative productivity shocks captures the fact that collateral-constrained agents receive less funding during recessions. In response to monetary contraction shocks, higher interest rates weaken the demand for borrowing and lower the value of φ_t.

The UIP deviation is associated with the spread between domestic and foreign interest rates, expected inflation of tradable goods, marginal rate of substitution of tradable consumption between the current period and the next period, as well as the tightening of collateral constraint. Fig. 4 panel (b) indicates that productivity shocks initially generate small differentials between domestic interest rates and foreign interest rates. Along with the consequences of lower tradable consumption (a higher marginal rate of substitution) and rising tradable inflation, productivity shocks bring a positive UIP deviation. Policy shocks resulting from raising domestic interest rates cause a significantly negative UIP deviation due to widened interest rate differentials, lower expected tradable inflation, and a lower intertemporal marginal rate of substitution in tradable consumption.

There are two forces accompanying the exchange rate shocks. First, positive exchange rate shocks drive foreign interest rates above domestic interest rates, increase expected tradable inflation, and reduce the intertemporal marginal rate of substitution in tradable consumption. Second, the shocks signal future appreciation of domestic currency and accordingly affect the first term on the right-hand side of Eq. (13). These two combined forces lead to a moderately negative UIP deviation.

5. Conclusions

Arbitrage demands capital and is involved with risks. Limited capital increases the arbitrage risks and causes unequal movement between interest rate differentials across two countries and exchange rate changes. Forward premium anomaly implies that high-interest-rate currencies will appreciate rather than depreciate. It receives attention because if a country's central bank raises the interest rate in order to curb inflation, future appreciation of domestic currency will make the policy less effective.

This paper links risk premium to a trader's capital constraint and employs DSGE modeling to examine the relationship between risk premiums and UIP deviations. Tightened liquidity to some degree restricts free capital movement and helps explain the forward premium anomaly. Our results corroborate the empirical finding that funding illiquidity gave rise to UIP violations in the midst of the 2008 financial crisis. Since the economic upheavals of 2008 and 2009, several central banks have injected massive liquidity into the funding markets. Our results also provide support for policy makers to take market participants' funding liquidity into account in the implementation of monetary policy.

Our research has several limitations. First, our model omits a banking sector. We discuss direct trading between the borrower and the lender. After including bank capital, the effect of a bank's balance sheet capacity on its lending decisions and asset prices can be examined. Second, exchange rates enter our model as exogenous shocks. Future research can endogenize the choice of different exchange rate systems and its impact on UIP deviations. As Jeanne and Rose (2002) propose, UIP deviations are smaller under fixed exchange rate regimes than under floating rate regimes. Determining whether a fixed exchange rate system involving a funding constraint magnifies UIP deviations remains for further investigation.

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